Digital Predistortion and Correction Techniques

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Outline

• Introduction
• Signal Properties
• Cartesian Loop
• Predistortion
  • Memory less systems
  • Memory based systems
  • Generic based predistortion
  • Piecewise predistortion
• Conclusions.
Power amplifier performance

\[ P_{IN} + P_{DC} = P_{DISS} + P_{OUT} \]
Long Term Evolution (LTE)

- 3GPP LTE → Downlink Data rate ≤ 100Mbps:
  - OFDM (QPSK, 16 QAM, and 64 QAM)
  - Various RF bandwidths: 1.4-20 MHz
  - Various Peak-to-Average-Power-Ratios (PAPR)
LTE RF signals

Channel Bandwidth [MHz]
Transmission Bandwidth Configuration [RB]
Transmission Bandwidth [RB]
Channel edge
Resource block
Active Resource Blocks
DC carrier (downlink only)

<table>
<thead>
<tr>
<th>Channel bandwidth ( BW_{channel} ) [MHz]</th>
<th>1.4</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPR [dB]</td>
<td>23</td>
<td>16.5</td>
<td>13.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MHz</td>
<td>50 RB</td>
<td>20 RB</td>
<td>6 RB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MHz</td>
<td>50 RB</td>
<td>20 RB</td>
<td>6 RB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4 MHz</td>
<td>6 RB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LTE linearity requirements

- The PA has to meet LTE linearity requirements

Spectral Mask

<table>
<thead>
<tr>
<th>Power (dB/MHz)</th>
<th>0</th>
<th>10</th>
<th>-1.0E+07</th>
<th>-5.0E+06</th>
<th>0.0E+00</th>
<th>5.0E+06</th>
<th>1.0E+07</th>
<th>1.5E+07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>0.0E+00</td>
<td>5.0E+06</td>
<td>1.0E+07</td>
<td>1.5E+07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modulation scheme for PDSCH</th>
<th>Required EVM [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>17.5 %</td>
</tr>
<tr>
<td>16QAM</td>
<td>12.5 %</td>
</tr>
<tr>
<td>64QAM</td>
<td>8 %</td>
</tr>
</tbody>
</table>

ACLR = 45dBc
Cartesian Loop Amplifier

\[ I_{IN} \rightarrow I_{ERROR} \rightarrow \Phi \rightarrow \text{Upconvert} \rightarrow \text{Output} \]

\[ Q_{IN} \rightarrow Q_{ERROR} \rightarrow \Phi \rightarrow \text{Downconvert} \rightarrow \text{Output} \]

\[ Q_{OUT} \rightarrow I_{OUT} \rightarrow \text{Upconvert} \rightarrow \text{Output} \]
Linearity improvement with pre-distortion

Characterization

Pre-distortion

Linear transfer function

AM-AM

\[ |V_{\text{OUT}}| \]

\[ |V_{\text{IN}}| \]

AM-PM

\[ \text{Arg(Gain)} \]

\[ |V_{\text{IN}}| \]

Pre-distorter

PA

Pre-distortion

Linear transfer function
Adaptive Baseband Predistortion

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Linearity characterisation

\[ V_{BB} = I_{BB} + j Q_{BB} \]

\[ V_{OUT} = I_{OUT} + j Q_{OUT} \]

\[ V_{IN} = (I_{IN} + j Q_{IN}) \exp(j\omega t) \]

\[ V_{OUT} = (I_{OUT} + j Q_{OUT}) \exp(j\omega t) \]

3GPP LTE, WiMax
ARB generator

Power Probe
Average \( P_{IN} \)

Power Probe
Average \( P_{OUT} \)

PA

Driver

Attenuators

VSA
PA static nonlinearities extraction

• Test signal: LTE (BW max 20MHz)
• In order to observe adjacent channels 1 and 2 we need 100 Msps as a sampling rate
• Input and output envelopes are acquired at two different access points in the measurement setup
  ⇒ Delay estimation.
  Is 10 ns resolution good enough?
• An LTE frame lasts 10ms
  ⇒ 1 Msamples.
  How many samples are really relevant?
• For memory-less polynomial behavioural modelling, which order can be considered?
PA static nonlinearities extraction: Delay estimation

- Class-F\(^{-1}\) PA response under a 10MHz LTE signal using two sampling speeds:
  - 100 Msps \(\Rightarrow\) 10 ns delay resolution
  - 326.4 Msps \(\Rightarrow\) 3 ns delay resolution

In the presence of a 10 MHz LTE signal, delay estimation is critical.
PA static nonlinearities extraction: Delay estimation

- Class-F\(^{-1}\) PA response under a 20MHz LTE signal sampled at 100Msps (blue) and up-sampled to 300Msps (red) and 500Msps (yellow):

  - Black solid lines curves $\Rightarrow$ memory-less polynomial fitting (9\(^{th}\) order) using **20000 samples**.
PA static nonlinearities extraction: waveform length effect

- Same data measurements: 20MHz LTE signal sampled at 100Msps (blue) and up-sampled to 300Msps (red) and 500Msps (yellow).

- Black solid lines curves ⇒ memory-less polynomial fitting (9th order) using **2000 samples**.

- Better/worst results are obtained with lower/higher polynomial orders.
_generic PA static nonlinearities extraction:*

- Extracting the pre-distortion parameters in presence of a simple probing signal with a **slow varying envelope (Generic Signal):**
  - Correct for “static” nonlinearities in order to meet LTE linearity requirements.
  - Assumption 1: The PA response under the Generic signal is similar to the one under LTE signals.
  - Assumption 2: Compensating for “static” nonlinearities is good enough

→ **The biggest benefit:** Coarse delay estimation
Assumptions verification

• Characterise a PA in the presence of a slow envelope generic signal similar to the 20 MHz LTE signal in terms of its statistics.
• Extract a generic pre-distortion function.
• Drive the previously obtained Benchmark Behavioural Model with the generically pre-distorted 20 MHz LTE signal.
• Assess the pre-distortion linearity improvement
Memory Pre-distortion based on generic PA characterization

- The realistic and generic signals should be similar in terms of:
  - Spectral content, bandwidth.
  - Peak-to-Average-Power-Ratio, PDF/CCDF.
- Multi-tones signals: compatible with LSNA techniques.
- From the FFT of the realistic signal, a reduced number of tones is used: The phase and magnitude of each selected tones remains the same the rest of tones are turned OFF.

Identify signal statistics such as PAPR and/or PDF and dynamics such as spectral content.
Memory-less Pre-distortion based on generic PA characterization

- Identify signal statistics such as PAPR and/or PDF
- Generate a probing signal such as random ramps, multi-tones
- Characterize the PA under the generic signal stimulus
- Apply the pre-distortion function to the generic signal
- Extract pre-distortion function

Linearity requirements satisfied

- Yes
- No

- Consider Memory

- Apply the pre-distortion function to the original signal
Memory Pre-distortion based on generic PA characterization

- Identify signal statistics such as PAPR and/or PDF and dynamics such as spectral content
- Generate a probing signal: multi-tones
- Characterize the PA under the generic signal stimulus
- Apply the predistortion function to the generic signal
- Extract predistortion function
- Apply the predistortion function to the original signal
- Consider Alternative Behavioural models for the predistorter

- Linearity requirements satisfied
  - Yes
  - No

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Generic PA static nonlinearities extraction:

PA response under generic and some 3GPP LTE excitation Class-F^-1, carrier frequency 900 MHz
Generic PA static nonlinearities extraction:

10MHz LTE

- Without pre-distortion
- Classic pre-distortion
- Generic pre-distortion
Generic probing signal characteristics: Random Ramp

- Periodic ramps with randomised peaks
  - Mimic some of LTE statistics
- Frequency = 500 kHz
Generic probing signal characteristics: 3-tones

- Three tones: Equal in magnitude, same phase
- Frequency spacing = 100 kHz
- Class-J PA

**AM-PM PA response**

**AM-AM PA response**
Multi-tones generation for generic characterization

- Maintaining the same magnitude and phase for the selected tones leads to a different signal statistics. ⇒ Eventually a decreasing PAPR.

- Initial number of tones 120000.
- Every curve corresponds to a halved number of tones.
Multi-tones generation for generic characterization

- Optimal curve corresponds to:
  - a number of tones = 5000.
  - PAPR error of 0.2dB.

- Setting all the magnitudes to the maximum one and maintaining the same phases for the selected tones leads to more controllability of the generic signal statistics.

⇒ Eventually, similar statistics to the realistic signal are obtained with smaller number of tones.
Pre-distortion of an LTE 10MHz signal: function obtained from the three tones characterization

<table>
<thead>
<tr>
<th>Tx Channel</th>
<th>Bandwidth</th>
<th>9.015 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjacent Channel</td>
<td>Bandwidth</td>
<td>7.68 MHz</td>
</tr>
<tr>
<td></td>
<td>Spacing</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Alternate Channel</td>
<td>Bandwidth</td>
<td>7.68 MHz</td>
</tr>
<tr>
<td></td>
<td>Spacing</td>
<td>20 MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power</th>
<th>4.23 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>-31.70 dB</td>
</tr>
<tr>
<td>Upper</td>
<td>-29.55 dB</td>
</tr>
</tbody>
</table>

EVM ≈ 7%

<table>
<thead>
<tr>
<th>Power</th>
<th>4.51 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>-45.38 dB</td>
</tr>
<tr>
<td>Upper</td>
<td>-47.01 dB</td>
</tr>
</tbody>
</table>

EVM ≈ 1%
Assumptions verification

Generic and classical Pre-distortion of a Class-F⁻¹ PA, carrier frequency 900 MHz

<table>
<thead>
<tr>
<th>PRE-DISTORTION METHOD</th>
<th>NMSE (dB)</th>
<th>ACPR left (dB)</th>
<th>ACPR right (dB)</th>
<th>Alternate ACPR left (dB)</th>
<th>Alternate ACPR right (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without pre-distortion</td>
<td>-</td>
<td>-34.44</td>
<td>-34.55</td>
<td>-57.4</td>
<td>-56.9</td>
</tr>
<tr>
<td>Classic Memory Pre-distortion</td>
<td>-46.6</td>
<td>-56.9</td>
<td>-57.6</td>
<td>-54.4</td>
<td>-57</td>
</tr>
<tr>
<td>Classic Memory-Less Pre-distortion</td>
<td>-29.2</td>
<td>-50</td>
<td>-52</td>
<td>-57</td>
<td>-60</td>
</tr>
<tr>
<td>Generic Pre-distortion</td>
<td>-28.9</td>
<td>-50.2</td>
<td>-49.8</td>
<td>-58</td>
<td>-60</td>
</tr>
</tbody>
</table>
Two channels of 20MHz LTE

Standard: E-UTRA/LTE Square

<table>
<thead>
<tr>
<th>Tx Channels</th>
<th>Adjacent Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch1 (Ref)</td>
<td>Lower -47.73 dB</td>
</tr>
<tr>
<td></td>
<td>Upper -47.54 dB</td>
</tr>
<tr>
<td>Ch2</td>
<td>Lower -47.60 dB</td>
</tr>
<tr>
<td></td>
<td>Upper -48.12 dB</td>
</tr>
</tbody>
</table>

Total 5.32 dBm
High linearity order fitting for high PAPR signals

- High efficiency PA architectures such as ET exhibit an high order nonlinear transfer function.
- Classical single fit can be unsuccessful in the presence of signals with high PAPR.
### Piece-wise pre-distortion (PW)

$$y(t) = \begin{cases} 
\sum_{i=1}^{\text{Poly}_1} \alpha_i \ x(t) \ |x(t)|^{i-1}, & |x(t)| < x_1 \\
\sum_{i=1}^{\text{Poly}_2} \beta_i \ x(t) \ |x(t)|^{i-1}, & x_1 \leq |x(t)| \leq x_2 \\
\sum_{i=1}^{\text{Poly}_3} \gamma_i \ x(t) \ |x(t)|^{i-1}, & |x(t)| > x_2 
\end{cases}$$

**Transfer function of the PA pre-distorter**

- **AM-AM**
- **AM-PM**

**Data points:**
- **o data**
- **- Classic PW fit**
Overlapped Segments Piece-wise pre-distortion (OSPW)

Ensuring the continuity between segments of the piece-wise polynomial fitting requires complex and significant computational resources. Allowing segments of the piece-wise polynomial fitting to overlap simplifies the way the continuity between segments is handled.
### OSPW assessment

<table>
<thead>
<tr>
<th>Number of Coefficients (Poly1,Poly2,Poly3)</th>
<th>ACLR [dBc]</th>
<th>ACLR Alternate [dBc]</th>
<th>EVM [%]</th>
<th>Output Power [dBm]</th>
<th>Drain Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
<td>QPSK</td>
<td>16-QAM</td>
<td>64-QAM</td>
</tr>
<tr>
<td>Single polynomial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-39.04</td>
<td>-38.71</td>
<td>-48.01</td>
<td>-47.75</td>
<td>2.03</td>
</tr>
<tr>
<td>7</td>
<td>-40</td>
<td>-39.93</td>
<td>-47.08</td>
<td>-46.74</td>
<td>1.78</td>
</tr>
<tr>
<td>8</td>
<td>-40.15</td>
<td>-40.25</td>
<td>-47.01</td>
<td>-46.80</td>
<td>1.61</td>
</tr>
<tr>
<td>9</td>
<td>-41.29</td>
<td>-41.35</td>
<td>-46.76</td>
<td>-46.61</td>
<td>1.53</td>
</tr>
<tr>
<td>10</td>
<td>-42.01</td>
<td>-42.13</td>
<td>-47.29</td>
<td>-47.33</td>
<td>1.45</td>
</tr>
<tr>
<td>11</td>
<td>-42.97</td>
<td>-43.19</td>
<td>-47.25</td>
<td>-47.90</td>
<td>1.31</td>
</tr>
<tr>
<td>12</td>
<td>-43.77</td>
<td>-43.94</td>
<td>-48.12</td>
<td>-48.27</td>
<td>1.28</td>
</tr>
<tr>
<td>13</td>
<td>-45.09</td>
<td>-45.54</td>
<td>-49.11</td>
<td>-49.22</td>
<td>1.22</td>
</tr>
<tr>
<td>Piece-wise polynomial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 (2,2,2)</td>
<td>-44.79</td>
<td>-45.48</td>
<td>-50.18</td>
<td>-50.16</td>
<td>1.28</td>
</tr>
<tr>
<td>7 (3,2,2)</td>
<td>-46.19</td>
<td>-47.16</td>
<td>-53.09</td>
<td>-53.35</td>
<td>1.23</td>
</tr>
<tr>
<td>8 (3,3,2)</td>
<td>-48.07</td>
<td>-50.43</td>
<td>-54.22</td>
<td>-54.44</td>
<td>1.13</td>
</tr>
<tr>
<td>9 (3,3,3)</td>
<td>-48.46</td>
<td>-50.66</td>
<td>-54.35</td>
<td>-54.57</td>
<td>1.12</td>
</tr>
<tr>
<td>10 (4,3,3)</td>
<td>-49.67</td>
<td>-52.63</td>
<td>-56.18</td>
<td>-56.44</td>
<td>1.05</td>
</tr>
<tr>
<td>11 (4,4,3)</td>
<td>-50.10</td>
<td>-52.64</td>
<td>-56.27</td>
<td>-56.54</td>
<td>1.06</td>
</tr>
<tr>
<td>12 (5,4,3)</td>
<td>-50.22</td>
<td>-53.12</td>
<td>-58.17</td>
<td>-58.31</td>
<td>1.08</td>
</tr>
<tr>
<td>13 (5,5,3)</td>
<td>-50.21</td>
<td>-53.44</td>
<td>-57.76</td>
<td>-58.10</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Note: The values in red indicate the best performance for each category.
Pre-distortion limitations

- Digital Pre-distortion (DPD) consists of cascading two nonlinear functions:

\[
|V_{IN}| \rightarrow |V_{OUT}| \\
\]

- Generally the less a PA is driven the less efficient it becomes.
Summary

• Generic PA characterization for PA pre-distortion:
  - memory-less compensation with coarse delay estimation.
  - Memory compensation with multi-tones

• Overlapped Piece Wise polynomial pre-distortion to accommodate high order PA nonlinearities in the presence of high PAPR signals.
Thank you!